6. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 6-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry sector. CO_2 emissions from on-farm energy use are accounted in the Energy chapter.

Figure 6-1: 2004 Agriculture Chapter Greenhouse Gas Emission Sources

In 2004, the agricultural sector was responsible for emissions of 440.1 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 6 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. CH_4 emissions from enteric fermentation and manure management represent about 20 percent and 7 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and agricultural residue burning were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 68 percent. Manure management and agricultural residue burning were also small sources of N_2O emissions.

Table 6-2 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2004, CH_4 emissions from agricultural activities increased by 2 percent while N_2O emissions decreased by 1 percent. In addition to CH_4 and N_2O, field burning of agricultural residues was also a minor source of the indirect greenhouse gases carbon monoxide (CO) and nitrogen oxides (NO_x).

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**156.8**	**164.2**	**164.0**	**162.0**	**161.9**	**161.5**	**161.9**	**160.4**
Enteric Fermentation	117.9	116.7	116.8	115.6	114.6	114.7	115.1	112.6
Manure Management	31.2	38.8	38.1	38.0	38.9	39.3	39.2	39.4
Rice Cultivation	7.1	7.9	8.3	7.5	7.6	6.8	6.9	7.6
Agricultural Residue Burning	0.7	0.8	0.8	0.8	0.8	0.7	0.8	0.9
N_2O	**282.7**	**319.0**	**299.1**	**296.5**	**301.5**	**296.2**	**277.1**	**279.7**
Agricultural Soil Management	266.1	301.1	281.2	278.2	282.9	277.8	259.2	261.5
Manure Management	16.3	17.4	17.4	17.8	18.1	18.0	17.5	17.7
Agricultural Residue Burning	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.5
Total	**439.6**	**483.2**	**463.1**	**458.4**	**463.4**	**457.8**	**439.1**	**440.1**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**7,468**	**7,821**	**7,810**	**7,713**	**7,710**	**7,693**	**7,712**	**7,640**
Enteric Fermentation	5,612	5,559	5,563	5,507	5,459	5,463	5,481	5,362
Manure Management	1,484	1,848	1,816	1,811	1,850	1,871	1,865	1,875
Rice Cultivation	339	376	395	357	364	325	328	360
Agricultural Residue Burning	33	38	37	38	37	34	38	42
N_2O	**913**	**1,029**	**965**	**956**	**972**	**956**	**894**	**902**
Agricultural Soil Management	858	971	907	897	913	896	836	844
Manure Management	52	56	56	58	58	58	57	57
Agricultural Residue Burning	1	1	1	1	1	1	1	2

CO	**689**	**789**	**767**	**790**	**770**	**706**	**796**	**877**
NO_x	**28**	**35**	**34**	**35**	**35**	**33**	**34**	**39**

Note: Totals may not sum due to independent rounding.

6.1. Enteric Fermentation (IPCC Source Category 4A)

CH_4 is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a by-product, which can be exhaled or eructated by the animal. The amount of CH_4 produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Among domesticated animal types, ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions among all animal types.

Non-ruminant domesticated animals (e.g., swine, horses, and mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affects CH_4 emissions. In general, lower feed quality or higher feed intake lead to higher CH_4 emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

CH_4 emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4. Total livestock CH_4 emissions in 2004 were 112.6 Tg CO_2 Eq. (5,362 gigagrams [Gg]), decreasing slightly since 2003 due to minor decreases in some animal populations and dairy cow milk production in some regions. Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2004. Emissions from dairy cattle in 2004 accounted for 24 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2004, emissions from enteric fermentation have decreased by 5 percent. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. During this timeframe, populations of sheep have decreased by an average annual rate of about 4 percent per year while horse populations have remained relatively constant and the population of goats has increased by an average of 2 percent per year.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1998	1999	2000	2001	2002	2003	2004
Beef Cattle	83.2	85.0	84.9	83.4	82.5	82.4	82.6	80.4
Dairy Cattle	28.9	26.3	26.6	27.0	26.9	27.1	27.3	27.0
Horses	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Sheep	1.9	1.3	1.2	1.2	1.2	1.1	1.1	1.0
Swine	1.7	2.0	1.9	1.9	1.9	1.9	1.9	1.9
Goats	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.3
Total	**117.9**	**116.7**	**116.8**	**115.6**	**114.6**	**114.7**	**115.1**	**112.6**

Note: Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	**1990**		**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Beef Cattle	3,961		4,047	4,045	3,973	3,928	3,923	3,934	3,830
Dairy Cattle	1,375		1,251	1,265	1,283	1,280	1,288	1,299	1,285
Horses	91		94	93	94	95	95	95	95
Sheep	91		63	58	56	55	53	51	49
Swine	81		93	90	88	88	90	90	91
Goats	13		12	12	12	12	13	13	13
Total	**5,612**		**5,559**	**5,563**	**5,507**	**5,459**	**5,463**	**5,481**	**5,362**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock emission estimates fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., Intergovernmental Panel on Climate Change [IPCC] Tier 2) was therefore applied to estimating emissions for all cattle except for bulls. Emission estimates for other domesticated animals (horses, sheep, swine, goats, and bulls) were handled using a less detailed approach (i.e., IPCC Tier 1).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
    - Calves
    - Heifer Replacements
    - Cows
- Beef Cattle
    - Calves
    - Heifer Replacements
    - Heifer and Steer Stockers
    - Animals in Feedlots (Heifers and Steers)
    - Cows
    - Bulls

Calf birth rates, end of year population statistics, detailed feedlot placement information, and slaughter weight data were used to model cohorts of individual animal types and their specific emissions profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.9. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (1995a,b; 1999a,c,d,f; 2000a,c,d,e; 2001a,c,d,f; 2002a,c,d,f; 2003a,c,d,f; 2004a,c,d,f, 2005a-d).

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values and CH_4 conversion rates (Y_m) for each population category. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for other well-fed cattle consuming temperate-climate feed types. Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed, rather than using the recommended IPCC values. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies, expert opinion, and modeling of animal physiology. The diet characteristics for dairy cattle were from Donovan (1999), while beef cattle were derived from NRC (2000). DE and Y_m for dairy cows were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. See Annex 3.9 for more details on the method used to characterize cattle diets in the United States.

To estimate CH_4 emissions from cattle, the population was divided into region, age, sub-type (e.g., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, and heifer and steer in feedlots), and production (e.g., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. Cattle diet characteristics were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, and heifer feedlot animals. To estimate emissions from cattle, population data were multiplied by the emission factor for each cattle type. More details are provided in Annex 3.9.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. CH_4 emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2004. Also, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle. Annual livestock population data for these other livestock types, except horses and goats, as well as feedlot placement information were obtained for all years from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a,c, 1998a-b, 1999a,b,e, 2000b, 2004a,b,e,g,h, 2005a,d-h). Horse population data were obtained from the FAOSTAT database (FAO 2005), because USDA does not estimate U.S. horse populations annually. Goat population data for 1992, 1997, and 2002 were obtained from the Census of Agriculture (USDA 2005i); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the *1992 and 1997 Census of Agriculture* (USDA 2005i). CH_4 emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC/UNEP/OECD/IEA 1997). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

See Annex 3.9 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty

Quantitative uncertainty of this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique. These estimates were developed for the 2001 inventory estimates. No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2004 activity data and emission factor input variables. Consequently, these uncertainty estimates were directly applied to the 2004 emission estimates.

A total of 185 primary input variables (178 for cattle and 8 for non-cattle) were identified as key input variables for uncertainty analysis. The normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run). For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources.

In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed as educated estimates.

The uncertainty ranges associated with the activity-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis (Table 6-5) indicate that, on average, in 19 out of 20 times (i.e., with 95 percent confidence), the total greenhouse gas emissions estimate from this source is within the range of approximately 100.2 to 132.9 Tg CO_2 Eq. (or that the actual CH_4 emissions are likely to fall within the range of approximately 11 percent below and 18 percent above the emission estimate of 112.6 Tg CO_2 Eq.). Among the individual sub-source categories, beef cattle account for the largest amount of CH_4 emissions as well as the largest degree of uncertainty in the inventory emission estimates. Consequently, the cattle sub-source categories together contribute to the largest degree of uncertainty in the inventory estimates of CH_4 emissions from livestock enteric fermentation. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates.

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2004 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a, b] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Enteric Fermentation	CH_4	112.6	100.2	132.9	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates and applied to 2004 estimates.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan. Tier 2 QA procedures included independent peer review of emission estimates. Particular emphasis was placed this year on cattle population and growth data, and on evaluating the effects of data updates as described in the recalculations discussion below.

Recalculations Discussion

While there were no changes in the methodologies used for estimating CH_4 emissions from enteric fermentation, emissions were revised slightly due to changes in data. USDA published revised population estimates which affected historical emissions estimated for swine, sheep, goats, and poultry. Recent historical emission estimates also changed for certain beef and dairy populations as a result USDA inputs and the calving rate described below.

The dairy cow calving rate represents the percentage of dairy cows that produced live calves in a specific year (the remainder either birthed dead calves or had reproductive problems). This value is used to determine the percentage of dairy cows that are pregnant during the specified month as well as the portion of total calf births that are from dairy cows. The previous model versions assumed a constant calving rate of 93.4 percent (USDA:APHIS:VS 1996). Research revealed more recent statistics (USDA:APHIS:VS 2002), that revised this calving rate to 88.8 percent for cows and heifers that produced live calves during 2001. Modeling assumptions were thus revised to use the historic (93.4 percent) calving rate for all years through 2000 and the updated rate (88.8 percent) for subsequent periods.

Changes to previously reported emissions are summarized by the following: Year 2001 total (dairy and beef) cattle CH_4 emissions changed by just 0.1 percent. For 2002, beef cattle CH_4 emissions increased 4 Gg (0.1 percent) while dairy cattle emissions decreased by 2 Gg (0.1 percent). An upward revision in historical goat populations from 1995 through for 2003 resulted in an increase in CH_4 emissions for each of those years. In 2003, this change affected emissions by less than 3 Gg (0.05 percent of total enteric fermentation emissions from all animals). Recent historical emission estimates for sheep and swine both changed (each by less than one half of one percent of respective 2003 emissions) as a result of the USDA revisions described above.

Planned Improvements

Continued research and regular updates are necessary to maintain a current model of cattle diet characterization, feedlot placement data, rates of weight gain and calving, among other data inputs. While EPA has no plans for methodological changes in the modeling framework, the opportunity exists to continue to refine the model's results through identifying and improving individual data inputs. Research is currently underway to identify updates of this nature.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. CH_4 is produced by the anaerobic decomposition of manure. N_2O is produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. A number of other factors related to how the manure is handled also affect the amount of CH_4 produced. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For example, CH_4 production generally increases with rising temperature and residency time. Also, for non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Although the majority of manure is handled as a solid, producing little CH_4, the general trend in manure management, particularly for large dairy and swine producers, is one of increasing use of liquid systems. In addition, use of daily spread systems at smaller dairies is decreasing, due to new regulations limiting the application of manure nutrients, which has resulted in an increase of manure managed and stored on site at these smaller dairies.

The composition of the manure also affects the amount of CH_4 produced. Manure composition varies by animal type, including the animal's digestive system and diet. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. For example, feedlot cattle fed a high-energy grain diet generate manure with a high CH_4-producing capacity. Range cattle fed a low energy diet of forage material produce manure with about 50 percent of the CH_4-producing potential of feedlot cattle manure. However, some higher energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal. Ultimately, a combination of diet types and the growth rate of the animals will affect the quantity and characteristics of the manure produced.

A very small portion of the total nitrogen excreted is expected to convert to N_2O in the waste management system. The production of N_2O from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For N_2O emissions to occur, the manure must first be handled aerobically where ammonia or organic nitrogen is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. For example, manure at cattle drylots is deposited on soil, oxidized to nitrite and nitrate, and has the potential to encounter saturated conditions following rain events.

Certain N_2O emissions are accounted for and discussed in the Agricultural Soil Management source category within the Agriculture sector. These are emissions from livestock manure and urine deposited on pasture, range, or paddock lands, as well as emissions from manure and urine that is spread onto fields either directly as "daily spread" or after it is removed from manure management systems (e.g., lagoon, pit, etc.).

Table 6-6 and Table 6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category. Estimates for CH_4 emissions in 2004 were 39.4 Tg CO_2 Eq. (1,875 Gg), 26 percent higher than in 1990. The majority of this increase was from swine and dairy cow manure, where emissions increased 32 and 38 percent, respectively. The increase in emissions from these animal types is primarily attributed to shifts by the swine and dairy industries towards larger facilities. Although national dairy animal populations have been generally decreasing, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country. These areas of concentration, such as California, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus the shift toward larger facilities is translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This shift was accounted for by incorporating state-specific weighted CH_4 conversion factor (MCF) values in combination with the 1992, and 1997 farm-size distribution data reported in the *Census of Agriculture* (USDA 2005g). From 2003 to 2004, there was a 0.6 percent increase in CH_4 emissions, due to minor shifts in the animal populations and the resultant effects on manure management system allocations. A description of the emission estimation methodology is provided in Annex 3.10.

Total N_2O emissions from manure management systems in 2004 were estimated to be 17.7 Tg CO_2 Eq. (57 Gg). The 9 percent increase in N_2O emissions from 1990 to 2004 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems, in favor of litter-based systems and high-rise houses. In addition, there was an overall increase in the population of poultry and swine from 1990 to 2004, although swine populations periodically declined slightly throughout the time series. N_2O emissions showed a 0.9 percent increase from 2003 to 2004, due to minor shifts in animal population.

The population of beef cattle in feedlots increased over the period of 1990 to 2004, resulting in increased N_2O emissions from this sub-category of cattle. Although dairy cow populations decreased overall for the period 1990 to 2004, the population of dairies managing and storing manure on-site—as opposed to using pasture, range, or paddock or daily spread systems—increased. Over the same period, dairies also experienced a shift to more liquid manure management systems at large operations, which result in lower N_2O emissions then dry systems. The net result is a slight decrease in dairy cattle N_2O emissions over the period 1990 to 2004. As stated previously, N_2O emissions from livestock manure deposited on pasture, range, or paddock land and manure immediately applied to land in daily spread systems are accounted for in the Agricultural Soil Management source category of the Agriculture sector.

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**31.2**	**38.8**	**38.1**	**38.0**	**38.9**	**39.3**	**39.2**	**39.4**
Dairy Cattle	11.4	13.9	14.1	14.5	15.0	15.1	15.7	15.7
Beef Cattle	3.2	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Swine	13.1	18.4	17.6	17.0	17.3	17.7	17.0	17.2
Sheep	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+
Poultry	2.7	2.7	2.6	2.6	2.7	2.7	2.7	2.7
Horses	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
N_2O	**16.3**	**17.4**	**17.4**	**17.8**	**18.1**	**18.0**	**17.5**	**17.7**
Dairy Cattle	4.3	3.9	4.0	3.9	3.9	3.9	3.9	3.8
Beef Cattle	4.9	5.5	5.6	5.9	6.1	5.9	5.6	5.7
Swine	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+
Poultry	6.3	7.2	7.2	7.2	7.3	7.4	7.3	7.4
Horses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Total	47.4		56.2	55.6	55.9	56.9	57.3	56.7	57.1

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-7: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990		1998	1999	2000	2001	2002	2003	2004
CH_4	**1,484**		**1,848**	**1,816**	**1,811**	**1,850**	**1,871**	**1,865**	**1,875**
Dairy Cattle	544		660	672	691	713	720	746	749
Beef Cattle	153		149	148	149	148	147	146	145
Swine	622		874	837	812	826	843	811	820
Sheep	9		6	6	5	5	5	5	5
Goats	1		1	1	1	1	1	1	1
Poultry	128		129	125	125	129	127	127	127
Horses	27		28	28	28	29	29	29	29
N_2O	**52**		**56**	**56**	**58**	**58**	**58**	**57**	**57**
Dairy Cattle	14		13	13	13	13	13	13	12
Beef Cattle	16		18	18	19	20	19	18	19
Swine	1		1	1	1	1	1	1	1
Sheep	+		+	+	+	+	+	+	+
Goats	+		+	+	+	+	+	+	+
Poultry	20		23	23	23	24	24	24	24
Horses	1		1	1	1	1	1	1	1

+ Does not exceed 0.5 Gg.
Note: Totals may not sum due to independent rounding.

Methodology

The methodologies presented in the IPCC *Good Practice Guidance* (IPCC 2000) form the basis of the CH_4 and N_2O emission estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state);
- Amount of nitrogen produced (excretion rate by animal type times animal population);
- Amount of volatile solids produced (excretion rate by animal type times animal population);
- CH_4 producing potential of the volatile solids (by animal type);
- Extent to which the CH_4 producing potential is realized for each type of manure management system (by state and manure management system, including the impacts of any biogas collection efforts);
- Portion of manure managed in each manure management system (by state and animal type); and
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems.

This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management for this inventory. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998d, 2000b) and EPA (ERG 2000a, EPA 2002a, 2002b). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a, USDA 2000c, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).

Next, MCFs and N_2O emission factors were determined for all manure management systems. MCFs for dry systems and N_2O emission factors for all systems were set equal to default IPCC factors for temperate climates (IPCC 2000). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation (see Annex 3.10 for detailed information on MCF derivations for liquid systems). The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of volatile solids from lagoon systems.

For each animal group, the base emission factors were weighted to incorporate the distribution of management systems used within each state to create an overall state-specific weighted emission factor. To calculate this weighted factor, the percent of manure for each animal group managed in a particular system in a state was multiplied by the emission factor for that system and state, and then summed for all manure management systems in the state.

CH_4 emissions were estimated using the volatile solids (VS) production for all livestock. For poultry and swine animal groups, for example, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. For most cattle groups, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Lieberman and Pape, 2005). The resulting VS for each animal group were then multiplied by the maximum CH_4 producing capacity of the waste (B_o) and the state-specific MCFs.

N_2O emissions were estimated by determining total Kjeldahl nitrogen (TKN)[1] production for all livestock wastes using livestock population data and nitrogen excretion rates based on measurements of excreted manure. For each animal group, TKN production was calculated using a national average nitrogen excretion rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. State-specific weighted N_2O emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

The data used to calculate the inventory estimates were based on a variety of sources. Animal population data for all livestock types, except horses and goats, were obtained from the United States Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-f). Horse population data were obtained from the FAOSTAT database (FAO 2005), because USDA does not estimate U.S. horse populations annually. Goat population data were obtained from the Census of Agriculture (USDA 2005g). Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service (NRCS) personnel (Lange 2000). Dairy cow and swine population data by farm size for each state, used for the weighted MCF and emission factor calculations, were obtained from the *Census of Agriculture*, which is conducted every five years (USDA 2005g).

Manure management system usage data for dairy and swine operations were obtained from USDA's Centers for Epidemiology and Animal Health (USDA 1996b, 1998d, 2000b) for small operations and from estimates for EPA's Office of Water regulatory effort for large operations (ERG 2000a; EPA 2002a, 2002b). Data for layers were obtained from a voluntary United Egg Producers' survey (UEP 1999), previous EPA estimates (EPA 1992), and USDA's Animal Plant Health Inspection Service (USDA 2000c). Data for beef feedlots were also obtained from EPA's Office of Water (ERG 2000a; EPA 2002a, 2002b). Manure management system usage data for other livestock were taken from previous estimates (EPA 1992). Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations, and data provided by those personnel. These organizations include state NRCS offices, state extension services, state universities, USDA National Agriculture Statistics Service (NASS), and other experts

[1] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

(Deal 2000, Johnson 2000, Miller 2000, Poe et al. 1999, Stettler 2000, Sweeten 2000, and Wright 2000). Additional information regarding the percent of beef steer and heifers on feedlots was obtained from contacts with the national USDA office (Milton 2000).

MCFs for liquid systems were calculated based on average ambient temperatures of the counties in which animal populations were located. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2004). County population data were calculated from state-level population data from NASS and county-state distribution data from the 1992, 1997, and 2002 Census data (USDA 2005g). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county population distribution data for 1993 through 1996 were extrapolated based on 1992 and 1997 data; county population data for 1998 through 2001 were extrapolated based on 1997 and 2002 data; and county population data for 2003 to 2004 were assumed to be the same as 2002.

The maximum CH_4 producing capacity of the VS, or B_o, was determined based on data collected in a literature review (ERG 2000b). B_o data were collected for each animal type for which emissions were estimated.

Nitrogen excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. VS excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for swine, poultry, bulls, and calves not on feed. In addition, VS production rates from Lieberman and Pape (2005) were used for dairy and beef cows, heifers, and steer for each year of the inventory. N_2O emission factors and MCFs for dry systems were taken from *Good Practice Guidance* (IPCC 2000).

Uncertainty

An analysis was conducted for the manure management emission estimates presented in EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* (EPA 2003a) to determine the uncertainty associated with estimating N_2O and CH_4 emissions from livestock manure management. Because no substantial modifications were made to the inventory methodology since the development of these estimates, it is expected that this analysis is applicable to the uncertainty associated with the current manure management emission estimates.

The quantitative uncertainty analysis for this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate N_2O and CH_4 emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-8. Manure management CH_4 emissions in 2004 were estimated to be between 32.3 and 47.3 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 18 percent below to 20 percent above the 2004 emission estimate of 39.4 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 14.9 and 21.9 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the 2004 emission estimate of 17.7 Tg CO_2 Eq.).

Table 6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2004 Emission Estimate ($\mathbf{Tg\ CO_2\ Eq.}$)**	**Uncertainty Range Relative to Emission Estimate[a]**			
			($\mathbf{Tg\ CO_2\ Eq.}$)		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Manure Management	CH_4	39.4	32.3	47.3	-18%	+20%
Manure Management	N_2O	17.7	14.9	21.9	-16%	+24%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

The primary factors that contribute to the uncertainty in emission estimates are a lack of information on the usage of various manure management systems in each regional location and the exact CH_4 generating characteristics of each type of manure management system. Because of significant shifts in the swine and dairy sectors toward larger farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates reflect these shifts in the weighted MCFs based on the 1992, 1997, and 2002 farm-size data. However, the assumption of a direct relationship between farm size and liquid system usage may not apply in all cases and may vary based on geographic location. In addition, the CH_4 generating characteristics of each manure management system type are based on relatively few laboratory and field measurements, and may not match the diversity of conditions under which manure is managed nationally.

The IPCC *Good Practice Guidance* (IPCC 2000) published a default range of MCFs for anaerobic lagoon systems of 0 to 100 percent, which reflects the wide range in performance that may be achieved with these systems. There exist relatively few data points on which to determine country-specific MCFs for these systems. In the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing CH_4 at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur. Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, a MCF methodology was developed that more closely matches observed system performance and accounts for the affect of temperature on system performance.

However, there is uncertainty related to this methodology. The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of VS from the management system. This factor is currently estimated based on data from anaerobic lagoons in temperate climates, and from only three systems. However, this methodology is intended to account for systems across a range of management practices. Future work in gathering measurement data from animal waste lagoon systems across the country will contribute to the verification and refinement of this methodology. It will also be evaluated whether lagoon temperatures differ substantially from ambient temperatures and whether the lower bound estimate of temperature established for lagoons and other liquid systems should be revised for use with this methodology.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high-rise houses promote sufficient aerobic conditions to warrant a lower MCF.

The default N_2O emission factors published in the IPCC *Good Practice Guidance* (IPCC 2000) were derived using limited information. The IPCC factors are global averages; U.S.-specific emission factors may be significantly different. Manure and urine in anaerobic lagoons and liquid/slurry management systems produce CH_4 at different rates, and would in all likelihood produce N_2O at different rates, although a single N_2O emission factor was used for both system types. In addition, there are little data available to determine the extent to which nitrification-denitrification occurs in animal waste management systems. Ammonia concentrations that are present in poultry and swine systems suggest that N_2O emissions from these systems may be lower than predicted by the IPCC default factors. At this time, there are insufficient data available to develop U.S.-specific N_2O emission factors; however, this is an area of on-going research, and warrants further study as more data become available.

Uncertainty also exists with the maximum CH_4 producing potential of VS excreted by different animal groups (i.e., B_o). The B_o values used in the CH_4 calculations are published values for U.S. animal waste. However, there are several studies that provide a range of B_o values for certain animals, including dairy and swine. The B_o values chosen for dairy assign separate values for dairy cows and dairy heifers to better represent the feeding regimens of these animal groups. For example, dairy heifers do not receive an abundance of high energy feed and consequently, dairy heifer manure will not produce as much CH_4 as manure from a milking cow. However, the data available for B_o values are sparse, and do not necessarily reflect the rapid changes that have occurred in this industry with respect to feed regimens.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Tier 2 activities focused on comparing estimates for the 2003 and 2004 Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. Manure nitrogen data were quality assured by comparing state-level data with bottom up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and waste management system type for the full time series, between national level estimates for nitrogen excreted and the sum of county estimates for the full time series.

Recalculations Discussion

No changes have been incorporated into the overall methodology for the manure management emission estimates. However, changes were made to the 2004 calculations involving animal population data. Animal population data were updated to reflect the final estimates reports from USDA NASS, and 2002 USDA Census of Agriculture data (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-g). The population data in the most recent final estimates reflect some adjustments due to USDA NASS review. For horses, state-level populations were estimated using the national FAO population data and the state distributions from the 1992, 1997, and 2002 Census of Agriculture.

This change resulted in an average annual increase of 0.6 Tg CO_2 Eq. (2 percent) in CH_4 emissions and an average annual increase of 0.1 Tg CO_2 Eq. (0.6 percent) in N_2O emissions from manure management for the period 1990 through 2004.

Planned Improvements

Although an effort was made to introduce the variability in VS production due to differences in diet for beef and dairy cows, heifers, and steer, further research is needed to confirm and track diet changes over time. A methodology to assess variability in swine VS production would be useful in future inventory estimates.

Research will be initiated into the estimation and validation of the maximum CH_4-producing capacity of animal manure (B_o), for the purpose of obtaining more accurate data to develop emission estimates.

The American Society of Agricultural Engineers proposed new standards for manure production characteristics in 2004. These data will be investigated and evaluated for incorporation into future estimates.

Currently, 2004 temperature data are not incorporated into the 2004 model for the estimates of MCFs; 2003 data were used for 2004. The temperature data will be updated in the next year's inventory.

The methodology to calculate MCFs for liquid systems will be examined to determine how to account for a maximum temperature in the liquid systems. Additionally, available research will be investigated to develop a relationship between ambient air temperature and temperature in liquid waste management systems in order to improve that relationship in the MCF methodology.

Currently, temperate zone MCFs are used for non-liquid waste management systems, including pasture, range, and paddock, daily spread, solid storage, and drylot operations. However, there are some states that have an annual average temperature that would fall below 15°C (i.e., classified as "cool" zones). Therefore, CH_4 emissions from certain non-liquid waste management systems may be overestimated; however, the difference is expected to be relatively small due to the low MCFs for all "dry" management systems. The use of both cool and temperate MCFs for non-liquid waste management systems will be investigated for future inventories.

The 2002 Census of Agriculture data became available in mid-2004 and have already been incorporated into animal population estimates. EPA will also incorporate these data into future estimates of waste management system usage data for swine and dairy. For these animal groups, the percent of waste by management system is estimated using data broken out by geographic region and farm. Farm-size distribution data reported in the 1992 and 1997 Census of Agriculture are currently used to determine the percentage of animals utilizing the various manure management systems; farm-size data from the 2002 Census of Agriculture will be incorporated into next year's inventory.

The development of the National Ammonia Emissions Inventory for the United States (EPA 2004) used similar data sources to the current estimates of emissions from manure management, and through the course of development of the ammonia inventory, updated waste management distribution data were identified. Future inventory estimates will incorporate these updated data.

6.3. Rice Cultivation (IPCC Source Category 4C)

Most of the world's rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil to develop. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants are dead so the primary CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with more shallow flooding depths. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding and weeding practices). The factors that determine the amount of organic material that is available to decompose (i.e., organic fertilizer use, soil type, rice variety,[2] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over an entire growing season because the total amount of CH_4 released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate, and ammonium sulfate) appear to inhibit CH_4 formation.

Rice is cultivated in eight states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, Oklahoma, and Texas. Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers utilize organic fertilizers in the form of rice residue from the previous crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields,

[2] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop. CH_4 emissions from ratoon crops have been found to be considerably higher than those from the primary crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow for the stubble to decay aerobically), the amount of organic material that is available for decomposition is considerably higher than with the first (i.e., primary) crop.

Rice cultivation is a small source of CH_4 in the United States (Table 6-9 and Table 6-10). In 2004, CH_4 emissions from rice cultivation were 7.6 Tg CO_2 Eq. (360 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2004, ranging from an annual decrease of 11 percent to an annual increase of 17 percent, there was an overall increase of 6 percent over the fourteen-year period, due to an overall increase in primary crop area.[3]

The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states. Price is the primary factor affecting rice area in Arkansas, as farmers will plant more of what is most lucrative amongst soybeans, rice, and cotton. Government support programs have also been influential by affecting the price received for a rice crop (Slaton 2001b, Mayhew 1997). California rice area is primarily influenced by price and government programs, but is also affected by water availability (Mutters 2001). In Florida, rice acreage is largely a function of the price of rice relative to sugarcane and corn. Most rice in Florida is rotated with sugarcane, but sometimes it is more profitable for farmers to follow their sugarcane crop with sweet corn or more sugarcane instead of rice (Schueneman 1997, 2001b). In Louisiana, rice area is influenced by government support programs, the price of rice relative to cotton, soybeans, and corn, and in some years, weather (Saichuk 1997, Linscombe 2001b). For example, a drought in 2000 caused extensive saltwater intrusion along the Gulf Coast, making over 32,000 hectares unplantable. The dramatic decrease in ratooned area in Louisiana in 2002 was the result of hurricane damage to that state's rice-cropped area. In Mississippi, rice is usually rotated with soybeans, but if soybean prices increase relative to rice prices, then some of the acreage that would have been planted in rice, is instead planted in soybeans (Street 1997, 2001b). In Missouri, rice acreage is affected by weather (e.g., rain during the planting season may prevent the planting of rice), the price differential between rice and soybeans or cotton, and government support programs (Stevens 1997, Guethle 2001b). In Oklahoma, the state having the smallest harvested rice area, rice acreage is limited to the areas in the state with the right type of land for rice cultivation. Acreage is limited to growers who can afford the equipment, labor, and land for this intensive crop (Lee 2003). Texas rice area is affected mainly by the price of rice, government support programs, and water availability (Klosterboer 1997, 2001b).

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1998	1999	2000	2001	2002	2003	2004
Primary	**5.1**	**5.8**	**6.3**	**5.5**	**5.9**	**5.7**	**5.4**	**6.0**
Arkansas	2.1	2.7	2.9	2.5	2.9	2.7	2.6	2.8
California	0.7	0.8	0.9	1.0	0.8	0.9	0.9	1.1
Florida	+	+	+	+	+	+	+	+
Louisiana	1.0	1.1	1.1	0.9	1.0	1.0	0.8	1.0
Mississippi	0.4	0.5	0.6	0.4	0.5	0.5	0.4	0.4
Missouri	0.1	0.3	0.3	0.3	0.4	0.3	0.3	0.3
Oklahoma	+	+	+	+	+	+	+	+
Texas	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.4
Ratoon	**2.1**	**2.1**	**2.0**	**2.0**	**1.7**	**1.1**	**1.5**	**1.6**
Arkansas	+	+	+	+	+	+	+	+
Florida	+	0.1	0.1	0.1	+	+	+	+
Louisiana	1.1	1.2	1.2	1.3	1.1	0.5	1.0	1.1

[3] The 11 percent decrease occurred between 1992 and 1993 and 2001 and 2002; the 17 percent increase happened between 1993 and 1994.

Texas	0.9	0.8	0.7	0.7	0.6	0.5	0.5	0.5
Total	**7.1**	**7.9**	**8.3**	**7.5**	**7.6**	**6.8**	**6.9**	**7.6**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1998	1999	2000	2001	2002	2003	2004
Primary	**241**	**279**	**300**	**260**	**283**	**274**	**255**	**284**
Arkansas	102	126	138	120	138	128	124	132
California	34	39	43	47	40	45	43	50
Florida	1	2	2	2	1	1	+	1
Louisiana	46	53	52	41	46	45	38	45
Mississippi	21	23	27	19	22	22	20	20
Missouri	7	12	16	14	18	15	15	17
Oklahoma	+	+	+	+	+	+	+	+
Texas	30	24	22	18	18	18	15	19
Ratoon	**98**	**98**	**95**	**97**	**81**	**52**	**73**	**77**
Arkansas	+	+	+	+	+	+	+	+
Florida	2	3	4	2	2	2	2	2
Louisiana	52	59	58	61	52	25	50	50
Texas	45	36	33	34	27	24	22	24
Total	**339**	**376**	**395**	**357**	**364**	**325**	**328**	**360**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) recommends utilizing harvested rice areas and area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to estimate annual CH_4 emissions from rice cultivation. This methodology is followed with the use of U.S.-specific emission factors derived from rice field measurements. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This approach is consistent with IPCC *Good Practice Guidance* (IPCC 2000).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11. Primary crop areas for 1990 through 2004 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987-1992* (USDA 1994), *Field Crops Final Estimates 1992-1997* (USDA 1998), *Field Crops Final Estimates 1997-2002 (USDA 2003), and Crop Production 2004 Summary* (USDA 2005). Harvested rice areas in Florida, which are not reported by USDA, were obtained from Tom Schueneman (1999b, 1999c, 2000, 2001a) and Arthur Kirstein (2003), Florida agricultural extension agents, Dr. Chris Deren (2002) of the Everglades Research and Education Centre at the University of Florida, and Gaston Cantens (2004, 2005), Vice President of Corporate Relations of the Florida Crystals Company. Harvested rice areas for Oklahoma, which also are not reported by USDA, were obtained from Danny Lee of the Oklahoma Farm Services Agency (2003, 2004, 2005). Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998 and 1999, when the ratooned area was less than 1 percent of the primary area (Slaton 1999, 2000, 2001a; Wilson 2002, 2003, 2004, 2005). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a), about 65 percent of the primary area in 1999 (Schueneman 2000), around 41 percent of the primary area in 2000 (Schueneman 2001a), about 60 percent of the primary area in 2001 (Deren 2002), about 54 percent of the primary area in 2002 (Kirstein 2003), about 100 percent of the primary area in 2003 (Kirstein 2004), and about 77 percent of the primary area in 2004 (Cantens 2005). In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, increased to approximately 40 percent in 2000, returned to 30 percent in 2001, dropped to 15 percent in 2002, rose to 35 percent in 2003, and returned to 30 percent in 2004 (Linscombe 1999, 2001a, 2002, 2003, 2004, 2005; Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the entire 1990 to 1999 period, increased to 50 percent in 2000 due to an early primary crop, and then decreased to 40 percent in 2001, 37 percent in 2002, 38 percent in 2003, and 35 percent in 2004 (Klosterboer 1999, 2000, 2001a, 2002, 2003; Stansel 2004, 2005). California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990-2004 (Guethle 1999, 2000, 2001a, 2002, 2003, 2004, 2005; Lee 2003, 2004, 2005; Mutters 2002, 2003, 2004, 2005; Street 1999, 2000, 2001a, 2002, 2003; Walker 2004, 2005).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990		1998	1999	2000	2001	2002	2003	2004
Arkansas									
Primary	485,633		600,971	657,628	570,619	656,010	608,256	588,830	629,300
Ratoon*	0		202	202	0	0	0	0	0
California	159,854		185,350	204,371	221,773	190,611	213,679	205,180	238,770
Florida									
Primary	4,978		8,094	7,229	7,801	4,562	5,077	2,315	5,077
Ratoon	2,489		4,047	4,673	3,193	2,752	2,734	2,315	2,734
Louisiana									
Primary	220,558		250,911	249,292	194,253	220,963	216,512	182,113	215,702
Ratoon	66,168		75,273	74,788	77,701	66,289	32,477	63,739	64,711
Mississippi	101,174		108,458	130,716	88,223	102,388	102,388	94,699	94,699
Missouri	32,376		57,871	74,464	68,393	83,772	73,654	69,203	78,915
Oklahoma	617		19	220	283	265	274	53	158
Texas									
Primary	142,857		114,529	104,816	86,605	87,414	83,367	72,845	88,223
Ratoon	57,143		45,811	41,926	43,302	34,966	30,846	27,681	30,878
Total Primary	***1,148,047***		***1,326,203***	***1,428,736***	***1,237,951***	***1,345,984***	***1,303,206***	***1,215,237***	***1,350,844***
Total Ratoon	***125,799***		***125,334***	***121,589***	***124,197***	***104,006***	***66,056***	***93,735***	***98,323***
Total	**1,273,847**		**1,451,536**	**1,550,325**	**1,362,148**	**1,449,991**	**1,369,262**	**1,308,972**	**1,449,167**

* Arkansas ratooning occurred only in 1998 and 1999.
Note: Totals may not sum due to independent rounding.

To determine what seasonal CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments which involved atypical or nonrepresenative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation), as well as experiments in which measurements were not made over an entire flooding season or floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results[4] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with added synthetic and organic fertilizer (Bossio et al. 1999; Cicerone et al. 1992; Sass et al. 1991a, 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

[4] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the reasons just mentioned. In addition, one measurement from the ratooned fields (i.e., the flux of 2.041 g/m^2/day in Lindau and Bollich 1993) was excluded since this emission rate is unusually high compared to other flux measurements in the United States, as well as in Europe and Asia (IPCC/UNEP/OECD/IEA 1997).

Uncertainty

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This inherent variability is due to differences in cultivation practices, in particular, fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 22 to 479 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. The uncertainty distributions around the primary and ratoon emission factors were derived using the distributions of the relevant primary or ratoon emission factors available in the literature and described above. Variability about the rice emission factor means were not normally distributed for either primary or ratooned crops, but rather skewed, with a tail trailing to the right of the mean, therefore a lognormal-type statistical distribution was applied in the Tier 2 Monte Carlo analysis.

Uncertainty regarding primary cropping area is an additional consideration. Uncertainty associated with primary rice-cropped area for each state was obtained from expert judgment, and ranged from 1 percent to 5 percent of the mean area. A normal distribution, truncated to avoid negative values, of uncertainty was assumed about the mean for areas.

Another source of uncertainty lies in the ratooned areas, which are not compiled regularly. Although ratooning accounts for only 5 to 10 percent of the total rice-cropped area, it is responsible for 15 to 30 percent of total emissions. For states that have never reported any ratooning, it is assumed that no ratooning occurred in 2004 with complete certainty. For states that regularly report ratooning, uncertainty is estimated to be between 3 percent and 5 percent (based on expert judgment) and is assumed to have a normal distribution, truncated to avoid negative values. For Arkansas, which reported ratooning in 1998 and 1999 only, a triangular distribution was assumed, with a lower boundary of 0 percent ratooning and an upper boundary of 0.034 percent ratooning based on the maximum ratooned area reported in 1998 and 1999.

A final source of uncertainty is in the practice of flooding outside of the normal rice season. According to agricultural extension agents, all of the rice-growing states practice this on some part of their rice acreage. Estimates of these areas range from 5 to 68 percent of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition. To date, however, CH_4 flux measurements have not been undertaken over a sufficient geographic range or under a broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Tier 2) uncertainty analysis was performed using the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-12. Rice cultivation CH_4 emissions in 2004 were estimated to be between 2.5 and 19.4 Tg CO_2 Eq. at a 95 percent confidence level (or 19 of 20 Monte Carlo Stochastic Simulations). This indicates a range of 67 percent below to 157 percent above the 2004 emission estimate of 7.6 Tg CO_2 Eq.

Table 6-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	CH_4	7.6	2.5	19.4	-67%	+157%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for rice cultivation was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and cropping seasons to attempt to identify any outliers or inconsistencies. No problems were found. In addition, this year calculation spreadsheets were linked directly to source data spreadsheets to minimize transcription errors, and a central, cross-cutting agricultural data spreadsheet was created to prevent use of incorrect or outdated data.

Recalculations Discussion

For the previous Inventory report, 2000 data for rice area harvested in Oklahoma were unavailable. Data were updated for the current Inventory based on information received from Lee (2005). This change resulted in a 0.02 percent increase in emission estimates for 2000 relative to the previous Inventory report.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[5] A number of agricultural activities increase mineral nitrogen (N) availability in soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities increase soil mineral N either directly or indirectly (see Figure 6-2). Direct increases occur through a variety of management practices that add or lead to greater release of mineral N in the soil, including fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and cultivation of organic soils (i.e., soils with a high organic matter content, otherwise known as histosols).[6] Other agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization in soils and thereby affect direct emissions. Indirect emissions occur through two pathways: 1) volatilization and subsequent atmospheric deposition of applied N;[7] and 2) surface runoff and leaching of applied N into groundwater and surface water. Direct emissions from agricultural lands (i.e., croplands and grasslands) are included in this section, while direct emissions from forest lands and settlements are presented in the Land Use, Land-Use Change, and Forestry chapter. However, indirect N_2O emissions due to anthropogenic activity on all land-use types (croplands, grasslands, as well as forest lands and settlements), are included in this section.

Figure 6-2: Direct and Indirect N_2O Emissions from Agricultural Soils

Agricultural soils are responsible for the majority of U.S. N_2O emissions. Estimated emissions from this source in 2004 were 261.6 Tg CO_2 Eq. (844 Gg N_2O) (see Table 6-13 and Table 6-14). Annual agricultural soil management N_2O emissions fluctuated between 1990 and 2004; however, overall emissions were 1.7 percent lower in 2004 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer

[5] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4) to nitrate (NO_3), and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well understood mechanism (Nevison 2000).

[6] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby enhancing N_2O emissions from these soils.

[7] These processes entail volatilization of applied N as ammonia (NH_3) and oxides of N (NO_x), transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate ammonium (NH_4), nitric acid (HNO_3), and NO_x.

use, and crop production.

Table 6-13: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Direct	**150.4**		**166.6**	**147.6**	**165.4**	**165.9**	**169.9**	**155.4**	**170.9**
Cropland	108.2		129.7	117.9	124.9	131.8	121.7	117.7	133.8
Grassland	42.2		36.9	29.6	40.5	34.2	48.2	37.7	37.2
Indirect (All Land-Use Types)*	**115.7**		**134.5**	**133.6**	**112.8**	**117.0**	**107.9**	**103.8**	**90.6**
Total	**266.1**		**301.1**	**281.2**	**278.2**	**282.9**	**277.8**	**259.2**	**261.5**

Note: Totals may not sum due to independent rounding.
*Includes cropland, grassland, forest land, and settlements.

Table 6-14: N_2O Emissions from Agricultural Soils (Gg)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Direct	**485**		**538**	**476**	**534**	**535**	**548**	**501**	**551**
Cropland	349		418	380	403	425	392	380	431
Grassland	136		119	96	131	110	155	122	120
Indirect (All Land-Use Types)*	**373**		**434**	**431**	**364**	**377**	**348**	**335**	**292**
Total	**858**		**971**	**907**	**897**	**913**	**896**	**836**	**844**

Note: Totals may not sum due to independent rounding.
*Includes cropland, grassland, forest land, and settlements.

Estimated direct and indirect N_2O emissions by sub-source category are provided in Table 6-15 and Table 6-16.

Table 6-15: Direct N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Cropland	**108.2**		**129.7**	**117.9**	**124.9**	**131.8**	**121.7**	**117.7**	**133.8**
Mineral Soils	105.3		126.8	115.1	122.0	128.9	118.8	114.8	130.8
Organic Soils	2.8		2.9	2.9	2.9	2.9	2.9	2.9	2.9
Grassland	**42.2**		**36.9**	**29.6**	**40.5**	**34.2**	**48.2**	**37.7**	**37.2**
Total	**150.4**		**166.6**	**147.6**	**165.4**	**165.9**	**169.9**	**155.4**	**170.9**

Note: Totals may not sum due to independent rounding.

Table 6-16: Indirect N_2O Emissions from all Land Use Types* (Tg CO_2 Eq.)

Activity	1990		1998	1999	2000	2001	2002	2003	2004
Volatilization and Atm. Deposition	16.2		17.8	17.2	18.0	17.5	17.7	17.7	17.3
Surface Leaching & Run-Off	99.5		116.7	116.5	94.8	99.5	90.2	86.0	73.3
Total	**115.7**		**134.5**	**133.6**	**112.8**	**117.0**	**107.9**	**103.8**	**90.6**

Note: Totals may not sum due to independent rounding.
*Includes cropland, grassland, forest land, and settlements.

Methodology

Current IPCC methods divide the N_2O source category into three components: 1) direct emissions from soils due to N additions to cropland and grassland mineral soils and from the drainage and cultivation of organic cropland soils; 2) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and 3) indirect emissions from soils and water induced by N additions and manure deposition to soils of all land-use types. The methodology used to estimate emissions from agricultural soil management in the United States is based on a combination of Tier 1 and 3 approaches as defined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997), and later amended in the IPCC *Good Practice Guidance* (IPCC 2000) and *Good Practice Guidance for Land Use, Land-Use Change, and Forestry* (IPCC 2003). Specifically, a Tier 3, process-based model (DAYCENT) is used to estimate direct emissions from major crops on mineral (i.e., non-organic) soils; as well as most of the direct emissions from grasslands. The DAYCENT-derived direct emissions from grasslands include emissions from deposition of PRP manure as well as several land management practices such as seeding with forage legumes. The Tier 1 IPCC methodology is used to estimate direct emissions from non-major crops on mineral soils; the portion of the grassland direct emissions from PRP and forage legume N additions that were not estimated with the Tier 3 DAYCENT model; and direct emissions from drainage and cultivation of organic cropland soils. A combination of DAYCENT and the IPCC Tier 1 method is used to estimate indirect emissions from soils. Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each component.

Direct N_2O Emissions from Agricultural Soils

Major Crop Types on Mineral Cropland Soils

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from mineral cropland soils producing major crops, specifically corn, soybean, wheat, alfalfa hay, other hay, sorghum, and cotton, which represent approximately 90 percent of total croplands in the United States. DAYCENT simulated crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions, and the simulations were driven by model input data generated from daily weather records (Thornton et al. 1997, 2000; Thornton and Running 1999), land management surveys (see citations below), and soil physical properties determined in national soil surveys (Soil Survey Staff 2005).

DAYCENT simulations were conducted for each major crop at the county scale in the United States. The county scale was selected because soil and weather data were available for every county with more than 100 acres of agricultural land. However, land management data (e.g., timing of planting, harvesting, and fertilizer application; intensity of cultivation, rate of fertilizer application) were only available at the agricultural region level as defined by the Agricultural Sector Model (McCarl et al. 1993). There are 63 agricultural regions in the contiguous United States; most states correspond to one region, except for those with greater heterogeneity in agricultural practices, in which there are further subdivisions. Therefore, while several cropping systems were simulated for each county in an agricultural region, the model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested, amount of fertilizer added), did not differ among the counties in an agricultural region.

Nitrous oxide emission estimates from DAYCENT include the influence of N additions, crop type, irrigation, and other factors in aggregate, and therefore it is not possible to partition N_2O emissions by anthropogenic activity (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). Consequently, emissions are not subdivided according to activity (e.g., N fertilization, manure amendments), as is suggested in the IPCC *Guidelines*, but the overall estimates are still more accurate than the more simplistic IPCC method, which is not capable of addressing the broader set of driving variables influencing N_2O emissions. Thus DAYCENT forms the basis for a more complete estimation of N_2O emissions than is possible with the IPCC methodology.

Nitrous oxide emissions from managed agricultural lands are the result of interactions between the combined anthropogenic interventions that are implemented (e.g., N fertilization and manure application) and natural background emissions of N_2O, which would occur regardless of anthropogenic management. To isolate anthropogenic emissions from natural background emissions of N_2O, DAYCENT was used to simulate emissions under potential native conditions for lands used to produce major crops, and the resulting estimates were subtracted from the N_2O emissions simulated under current crop management. The reported estimates of emissions from managed soils therefore represent the difference between simulated emissions from potential native conditions and emissions from cropland soils.

With these methods, DAYCENT was used to estimate direct N_2O emissions due to increased mineral N availability for the following practices: 1) the application of synthetic and organic commercial fertilizers, 2) the application of livestock manure, 3) the production of N-fixing crops, and 4) the retention of crop residues (i.e., leaving residues in the field after harvest). For each of these practices, annual increases in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: Alexander and Smith (1990), Anonymous (1924), Battaglin and

Goolsby (1994), Engle and Makela (1947), ERS (1994, 2003), Fraps and Asbury (1931), Ibach and Adams (1967), Ibach et al. (1964), NFA (1946), NRIAI (2003), Ross and Mehring (1938), Skinner (1931), Smalley et al. (1939), Taylor (1994), USDA (1966, 1957, 1954, 1946).

- Managed manure production and application to croplands and grasslands: Manure N amendments were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). These values were adjusted for other years based on manure N production. Data sources to estimate manure production include USDA (1994b-c, 1995a-b, 1998a, 1998c, 1999a-c, 2000a, 2004a-e, 2005a-g), FAO (2005), Lange (2000), Poe et al. (1999), Anderson (2000), Deal (2000), Johnson (2000), Miller (2000), Milton (2000), Stettler (2000), Sweeten (2000), Wright (2000), Safley et al. (1992). Managed manure N production was adjusted for the amount of manure used for feed. Even with this adjustment, a portion of the remaining managed manure N was not applied to crop and grassland soils according to Edmonds et al. (2003). The difference between manure N applied to soils and remaining N in the managed manure was assumed to be lost through volatilization of N species during handling and storage. Instead of assuming that 10 percent of synthetic and 20 percent of organic N applied to soils is volatilized and 30 percent of applied N was leached/runoff as with IPCC methodology, volatilization and N leaching/runoff from manure that was amended to soils was internally calculated by the DAYCENT process-based model.

- Nitrogen-fixing crops and forages and retention of crop residue: The IPCC approach considers this information as separate activity data. However, they are not considered separate activity data for the DAYCENT simulations because residue production and N fixation are internally generated by the model. In other words, DAYCENT accounts for the influence of N fixation and retention of crop residue on N_2O emissions, but these are not model inputs.

- Historical and modern crop rotation and management information (e.g., timing and type of cultivation, timing of planting/harvest, etc.): Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2004f), USDA (2000b) as extracted by Eve (2001) and revised by Ogle (2002), CTIC (1998), Piper et al. (1924), Hardies and Hume (1927), Holmes (1902, 1929), Spillman (1902, 1905, 1907, 1908), Chilcott (1910), Smith (1911), Kezer (ca. 1917), Hargreaves (1993), ERS (2002), Warren (1911), Langtson et al. (1922), Russell et al. (1922), Elliot and Tapp (1928), Elliot (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliot (1931), Brenner et al. (2002, 2001), Smith et al. (2002).

DAYCENT was used to simulate the influence of anthropogenic activity due to all of these activities, generating the U.S. estimate of direct N_2O emissions from mineral soils producing major crop types. Because the model is sensitive to actual interannual variability in weather patterns and other controlling variables, emissions associated with individual activities vary through time even if the management practices remain the same (e.g., if N fertilization remains the same for two years), rather than having a linear, monotonic response, which would occur using the IPCC method. The ability of DAYCENT to capture these interactions is largely the reason for more accurate estimates of N_2O emissions, compared to the more simplistic IPCC Tier 1 approach.

Mineral N was subject to volatilization and leaching/runoff according to the climatic conditions, soil type and condition, crop type, and land management practices such as cultivation and irrigation, as simulated by DAYCENT. The resulting amounts were then applied in the calculation of indirect emissions as described below (i.e., in the section entitled Indirect N_2O Emissions from Managed Soils of All Land-Use Types).

Non-Major Crop Types on Mineral Cropland Soils

For mineral cropland soils producing non-major crop types, the Tier 1 IPCC methodology was used to estimate direct N_2O emissions. Estimates of direct N_2O emissions from N applications to non-major crop types were based on the annual increase in mineral soil N from the following practices: 1) the application of synthetic commercial fertilizers, 2) the production of N-fixing crops, and 3) the retention of crop residues. No organic amendments (i.e., manure N, other organic commercial fertilizers) were considered here because they were assumed to be applied to crops simulated by DAYCENT. This assumption is reasonable because DAYCENT simulations included the 5 major cropping systems (corn, hay, sorghum, soybean, wheat), which are the land management systems receiving the vast majority (approximately 95 percent) of manure applications to cropped land in the United States (Kellogg et al. 2000, Edmonds et al. 2003), and manure accounts for approximately 95 percent of total organic amendments.

Annual synthetic fertilizer N additions to non-major crop types were calculated by process of elimination. For each year, fertilizer amounts for each of the following were summed: fertilizer applied to major crops (as simulated by DAYCENT—approximately 75 percent of the U.S. total), fertilizer applied to forest lands (less than 1 percent of the U.S. total), and fertilizer applied in settlements (approximately 10 percent of the U.S. total). The sum was then subtracted from total fertilizer use in the United States. This difference, approximately 15 percent of total synthetic fertilizer N used in the United States, was assumed to be applied to non-major crop types. Non-major crop types include: a) fruits, nuts, and vegetables, which were estimated to receive approximately 5 percent of total U.S. N fertilizer use (TFI 2000); and b) other annual crops not simulated by DAYCENT (barley, oats, tobacco, sugarcane, sugar beets, sunflower, millet, peanuts, etc.), which account for approximately 10 percent of total U.S. fertilizer use. The non-volatilized portion was obtained by multiplying the amount of fertilizer added to non-major crop types by the default IPCC volatilization fraction (IPCC/UNEP/OECD/IEA 1997, IPCC 2000). In addition to synthetic fertilizer N, N in soils due to the cultivation of non-major N-fixing crops (e.g., edible legumes) was included in these estimates. Finally, crop residue N was derived from information on crop production yields, residue management (retained vs. burned or removed), mass ratios of aboveground residue to crop product, dry matter fractions, and N contents of the residues (IPCC/UNEP/OECD/IEA 1997). The activity data for these practices were obtained from the following sources:

- Annual production statistics for crops whose residues are left on the field: USDA (1994a, 1998b, 2000c, 2001, 2002, 2003), Schueneman (1999, 2001), Deren (2002), Schueneman and Deren (2002), Cantens (2004), Lee (2003, 2004).

- Mass ratios of aboveground residue to crop product, dry matter fractions, and N contents for N-fixing crops: Strehler and Stützle (1987), Barnard and Kristoferson (1985), Karkosh (2000), Ketzis (1999), IPCC/UNEP/OECD/IEA (1997).

- Aboveground residue to crop mass ratios, residue dry matter fractions, and residue N contents of non-N fixing crops: Strehler and Stützle (1987), Turn et al. (1997), Ketzis (1999), Barnard and Kristoferson (1985), Karkosh (2000).

The total increase in soil mineral N from applied fertilizers, N-fixing crops, and crop residues was multiplied by the IPCC default emission factor to derive an estimate of cropland direct N_2O emissions from non-major crop types.

Drainage and Cultivation of Organic Cropland Soils

The IPCC Tier 1 method was used to estimate direct N_2O emissions from the drainage and cultivation of organic cropland soils. Estimates of the total U.S. acreage of drained organic soils cultivated annually for temperate and sub-tropical climate regions were obtained for 1982, 1992, and 1997 from the Natural Resources Inventory (USDA 2000b, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1994, 1998). These areas were linearly interpolated and extrapolated to estimate areas for the missing years. To estimate annual emissions, the total temperate areas were multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical areas were multiplied by the average of the IPCC default emission factors for temperate and tropical regions.

Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and IPCC Tier 1 methods were combined to estimate emissions from grasslands. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grasslands that are not intensively managed, while pastures are often seeded grasslands, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate N_2O emissions from grasslands at the county scale resulting from manure deposited by livestock directly onto the pasture (i.e., Pasture/Range/Paddock manure; which is simulated internally within the model), N fixation from legume seeding, sewage sludge amendments, managed manure amendments (i.e., manure other than PRP manure), and synthetic fertilizer application. The simulations used the same weather and soils data as discussed under the section for Major Crop Types. Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using managed manure N production data according to methods described under the Methodology Section for Major Crop Types. Sewage sludge was assumed to be applied on grasslands because of the heavy metal content and other pollutants in human waste that limits its use as an amendment to croplands. Sewage sludge was estimated from data compiled by EPA (1993, 1997, 1999, 2003), Bastian (2002, 2003, 2005), and Metcalf and Eddy (1991). DAYCENT generated per area estimates of N_2O emissions (g N_2O-N m^{-2}) from pasture and rangelands, which were then scaled to the entire county by multiplying the emissions estimate by reported pasture and rangeland areas in the county; summing results across all counties produced the national estimate. Grassland area data were obtained from the National Resources Inventory (USDA 2000b). The 1997 NRI data for pastures and rangeland were aggregated to the county level to estimate the grassland areas for 1995 to 2004, and the 1992 NRI pasture and rangeland data were aggregated to the county level to estimate areas from 1990 to 1994.

Manure N additions from grazing animals are modeled internally within the DAYCENT. Comparisons with estimates of total manure deposited on PRP (see Annex 3.11) showed that DAYCENT accounted for approximately 75 percent of total PRP manure. It is reasonable that DAYCENT did not account for all PRP manure because the NRI data do not include all grassland areas, such as federal grasslands. N_2O emissions from the portion of PRP manure N not accounted for by DAYCENT were estimated using the IPCC Tier 1 method with default emission factors (IPCC/UNEP/OECD/IEA 1997). Fixed N additions from forage legumes are also model outputs generated by DAYCENT. Comparisons with estimates of total N fixation by forage legumes showed that DAYCENT accounted for approximately 52 percent of total forage legume fixation. N_2O emissions from the portion of fixed legume N not accounted for by DAYCENT were estimated using the IPCC Tier 1 method with default emission factors (IPCC/UNEP/OECD/IEA 1997). Emission estimates from DAYCENT and the IPCC method were summed to provide total national emissions for grasslands in the United States.

Total Direct N_2O Emissions from Cropland and Grassland Soils

Annual direct emissions from major and non-major crops on mineral cropland soils, from drainage and cultivation of organic cropland soils, and from grassland soils were summed to obtain total direct N_2O emissions from agricultural soil management (see Table 6-13 and Table 6-14).

Indirect N_2O Emissions from Managed Soils of all Land-Use Types

This section describes methods for estimating indirect soil N_2O emissions from all land-use types (i.e., croplands, grasslands, forest lands, and settlements). Indirect N_2O emissions occur when mineral N made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH_3 following application of synthetic fertilizer or organic amendments (e.g., manure, sewage sludge), or deposition of PRP manure, or during storage, treatment, and transport of managed manure. Through atmospheric deposition, volatilized nitrogen can be returned to soils, and a portion is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil mineral N (primarily in the form of nitrate [NO_3^-]) that was made available through anthropogenic activity. The nitrate is subject to denitrification in water bodies, which leads to additional N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes agriculture, forestry, and other land-use activities.

N Transport from Managed Soils

Similar to the direct emissions calculation, several approaches were combined to estimate the amount of applied N that was exported from application sites through volatilization, and leaching and surface runoff. DAYCENT was used to simulate the amount of N transported from major cropland types and grasslands as NO_x and NH_3 through volatilization, and as NO_3 in leachate and runoff. N transport from non-major croplands, settlements, forest lands, and grasslands not accounted for by DAYCENT (i.e., from land areas that were not simulated with DAYCENT) were obtained by applying the IPCC default fractions for volatilization and for leaching and runoff to total fertilizer and manure N amounts applied or deposited on to these lands. Manure N from managed systems assumed to be volatilized during storage, treatment, and transport was also estimated and included as a source of N for indirect emissions.

Indirect N_2O Emissions from N Transport

The N transport from managed soils and from storage, treatment, and transport of managed manure were summed for both volatilization and leaching or surface runoff. The IPCC default emission factors for indirect N_2O were applied to the respective total amounts of N for each pathway to estimate emissions and then summed to obtain the total indirect N_2O emissions due to the use and management of U.S. croplands, grasslands, forest lands, and settlements (Table 6-16).

Uncertainty

Uncertainty was estimated differently for each of the following three components of N_2O emissions from agricultural soil management: 1) Direct emissions calculated by DAYCENT; 2) Direct emissions not calculated by DAYCENT; and 3) Indirect emissions.

For direct emissions calculated using DAYCENT, uncertainty was associated with the activity data, the model inputs, and the structure of the model (i.e., underlying model equations and parameterization). Uncertainties in activity data were evaluated based on variation in weather patterns, soil characteristics, and N application rates associated with crop types, years, and agricultural regions. Total uncertainty in N inputs was estimated to contribute 20 percent to the uncertainty in N_2O estimates (Mosier 2004); uncertainties in weather patterns contributed 19 percent (Thornton et al. 2000), and variation in soil characteristics contributed an additional 12 percent (Del Grosso 2005). Their combined uncertainty is approximately 30.1 percent using the sum-of-squares method. To estimate the uncertainty associated with the model structure, an effective emission factor was computed from DAYCENT outputs and compared with N_2O measurements from various cropped soils over the annual cycle (Del Grosso et al. 2005). The uncertainty associated with the effective emission factor was estimated at 57 percent (Del Grosso 2005). Simple error propagation led to an overall uncertainty for direct emissions of ±64 percent. Direct N_2O emissions not calculated by DAYCENT were assumed to have similar uncertainties and assigned the same value of ±64 percent.

Indirect emissions from agricultural soil management, which were calculated according to the default IPCC methodology, were estimated to have an uncertainty of ±286 percent (EPA 2004).

The results of the uncertainty analysis are summarized in Table 6-17. Agricultural soil management N_2O emissions in 2004 were estimated to be between 47.1 and 475.9 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 82 percent above and below the 2004 emission estimate of 261.6 Tg CO_2 Eq.

Table 6-17: Tier 1 Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2004 (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2004 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty (%)**	**Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)**	
				Lower Bound	**Upper Bound**
Agricultural Soil Management	N_2O	261.5	82%	47.1	475.9

Recalculations Discussion

Minor changes were made from previous reports, including adjustments in activity data and the use of a revised version of the DAYCENT model. The residue N fractions for dry edible beans, dry edible peas, Austrian winter peas, lentils, and wrinkled seed peas were revised to 0.0168. The source of activity data for pasture and rangelands was changed from NASS, which only provides partial accounting of pasture land area, to the National Resources Inventory, which provides county-level estimates for both pasture and rangelands for the entire country. This resulted in DAYCENT accounting for a larger portion of total grassland than last year. Also, a different soils database was used this year. Last year, the VEMAP 0.5^o resolution cell that contains the geographic center of each county was identified, and the dominant soil type was extracted and applied across the county. This year, surface soil texture and depth from the STATSGO soil map unit that intersected the geographical center of the largest cluster of agricultural land in each county was extracted and used for the simulations. Sewage sludge was simulated as an application to croplands in the previous year's inventory. However, croplands are less likely to be amended with sewage sludge due to the heavy metal content and other toxins associated with human waste. Therefore, in the current inventory, sewage sludge amendments to agricultural lands were simulated as an application to grasslands. Regarding the model revision, DAYCENT was modified to more realistically represent the grain filling period for crops (anthesis), and different cultivars of corn and soybean were simulated in various regions of the country to better represent the life span of the plants, particularly the days to maturity.

These changes, summarized in Table 6-18, resulted in an increase in emissions estimates for all years, ranging from an increase of 2 percent to 26 percent.

Table 6-18: Changes and Percent Difference in N_2O Emission Estimates for Agricultural Soil Management (Tg CO_2 Eq. and Percent)

Year	1990-2003 Inventory	1990-2004 Inventory	Percent Difference
1990	253.0	266.1	5.2
1991	247.6	278.5	12.5
1992	233.2	252.5	8.3
1993	247.6	312.7	26.3
1994	238.3	261.5	9.7
1995	244.7	308.1	25.9
1996	267.3	314.4	17.6
1997	252.0	276.6	9.7
1998	267.7	301.1	12.5
1999	243.4	281.2	15.5
2000	263.9	278.2	5.4
2001	257.1	282.9	10.0
2002	252.6	277.8	10.0
2003	253.5	259.2	2.2

[BEGIN BOX]

Box 6-1. Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The IPCC methodology used here is an example of a Tier 1 approach (IPCC/UNEP/OECD/IEA 1997), in which activity data from different N sources (e.g., synthetic fertilizer, manure, N fixation, etc.) are multiplied by the appropriate default IPCC emission factors to estimate N_2O emissions on a source by source basis. The Tier 3 approach used here utilizes a process-based model (i.e., DAYCENT) and is based on the environmental conditions at a specific location in addition to the N inputs. Consequently, it is necessary to not only know the amount of N inputs but the conditions under which the anthropogenic activity is increasing mineral N in a soil profile. The Tier 1 approach requires a minimal amount of activity data that is generally readily available in most countries (total N applied to crops), calculations are simple, and the methodology is highly transparent. In contrast, the Tier 3 approach requires more refined activity data (e.g., crop specific N amendment rates, daily climate, soil class, etc.), considerable computational resources and programming expertise, and the methodology is less transparent. The advantage of the Tier 3 approach is that the accuracy of estimates is expected to be greater using the advanced model, which accounts for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics). Emissions due to anthropogenic activity may be enhanced or dampened, depending on the specific environmental conditions. Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year; e.g., N added as fertilizer or through fixation contributes to N_2O emission for that year, but cannot be stored in soils and contribute to N_2O emission in subsequent years. In contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N is mineralized from soil organic matter and emitted as N_2O during subsequent years. The Tier 1 approach also assumes that only N from fertilizer and organic matter additions contributes to indirect N_2O emissions whereas the Tier 3 approach assumes that once N is in the plant/soil system, including residue N and soil organic matter, it can be cycled and lost through the two indirect pathways which contribute to N_2O emissions. Overall, the Tier 3 approach in this analysis (DAYCENT) estimates higher indirect emissions and lower direct emissions than IPCC methodology, particularly for N-fixing crops. This was primarily because of greater losses through volatilization and through leaching and surface runoff than was estimated using the IPCC Tier 1 methodology. For example, in 2004 direct soil N_2O emissions from agricultural sources were 225 vs. 171 Tg CO_2 Eq. for IPCC and DAYCENT/IPCC methodologies while indirect emissions from all sources were 80 and 91 Tg CO_2 Eq. for IPCC and DAYCENT/IPCC.

[END BOX]

QA/QC and Verification

For quality control, DAYCENT results for N_2O emissions and NO_3 leaching were compared with field data representing various cropped/grazed systems, soils types, and climate patterns. N_2O measurement data were available for seven sites in the United States and one in Canada, representing 25 different combinations of fertilizer treatments and cultivation practices. NO_3 leaching data were available for three sites in the United States representing nine different combinations fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.74 and 0.96 for annual N_2O emissions and NO_3 leaching, respectively.

Spreadsheets containing input data required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked and no errors were found. Spreadsheets containing input data and emission factors required for the Tier 1 approach used for non-major crops and grasslands not simulated by DAYCENT were checked and no errors were found. However, assumptions on the application of sewage sludge were questioned during the review process. A corrective action was taken to apply sewage sludge to grasslands in the simulations, rather than croplands, which are unlikely to receive sewage sludge due its high metal content and other toxins. Total emissions and emissions from the different categories were compared with inventories from previous years and differences were consistent with the methodological differences (see Recalculations section for further discussion).

Planned Improvements

Four major improvements are planned for the soil N_2O inventory. The first improvement will be to incorporate land survey data from the National Resources Inventory (NRI) (USDA 2000b) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture which are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1982 for all U.S. agricultural land, which is estimated at about 386 Mha. NASS is used as the basis for land-use records in the current inventory; the major disadvantage to this land survey is that most crops are grown in rotation, and NASS data provide no information regarding rotation histories.

In contrast, NRI is designed to track rotation histories, and this is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Moreover, the current inventory based on NASS does not quantify the influence of land-use change on emissions, which can be addressed using the NRI survey records. NRI also provides additional information on pasture land management that can be incorporated into the analysis (particularly the use of irrigation). Using NRI data will also make the N_2O inventory methods more consistent with those used to estimate net C fluxes for agricultural soils.

The second planned improvement will be to achieve consistency in N fertilization rates and organic amendments between the soil C and soil N_2O inventories. Currently, each inventory is using a combination of shared and different sources to model these activities. As part of this activity, manure amendments will be more realistically distributed among major crops, non-major crop types, and grasslands, according to methods used in the soil C inventory (see Annex 3.13). The goal will be to ensure that each is using the most accurate information in a consistent manner.

The third planned improvement is to develop a more rigorous uncertainty analysis. The current analysis is incomplete because there are additional uncertainties in activity data that were not addressed, such as N input rates, variation in county level weather patterns, and soil characteristics. For example, a single soil and climate type were used in the simulations for each county, but there can be considerable heterogeneity in these environmental variables. Consequently, there is inherent uncertainty in the current emission estimates which is not addressed. A Monte Carlo approach will be used to capture uncertainty in soil and weather input data at the county scale, as well as further elaboration of uncertainties from N inputs due to fertilization and organic amendments. The analysis will also address uncertainties in other key soil management practices such as irrigation and tillage histories. Uncertainties in the DAYCENT model structure will be further evaluated to address bias, which is not included in the effective emission factor analysis. Also, a more rigorous methodology will be developed for the IPCC Tier 1 calculations.

The fourth planned improvement deals with emissions from native rangelands. Emissions from unimproved rangelands with low to moderate grazing intensities are not much higher than emissions under native conditions. Subtracting the native land emissions is likely to underestimate the anthropogenic influence on emissions rates from rangelands, which are controlled by livestock grazing regimes. Therefore, future inventories will be modified to avoid subtracting native grassland emissions from simulations of livestock grazing in rangelands.

6.5. Field Burning of Agricultural Residues (IPCC Source Category 4F)

Large quantities of agricultural crop residues are produced by farming activities. A variety of ways exist to utilize or dispose of these residues. For example, agricultural residues can be left on or plowed back into the field, composted and then applied to soils, landfilled, or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, supplemental animal feed, or construction material. Field burning of crop residues is not considered a net source of CO_2, because the carbon released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts. Of these residues, less than 5 percent is burned each year, except for rice.[8] Annual emissions from this source over the period 1990 through 2004 have remained relatively constant, averaging approximately 0.7 Tg CO_2 Eq. (36 Gg) of CH_4, 0.4 Tg CO_2 Eq. (1 Gg) of N_2O, 746 Gg of CO, and 32 Gg of NO_x (see Table 6-19 and Table 6-20).

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[8] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Methodology" discussion below).

Table 6-19: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**0.7**	**0.8**	**0.8**	**0.8**	**0.8**	**0.7**	**0.8**	**0.9**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.3	0.3	0.3	0.4	0.3	0.3	0.4	0.4
Barley	+	+	+	+	+	+	+	+
Soybeans	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+	+	+
N_2O	**0.4**	**0.5**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+	+
Soybeans	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.3
Peanuts	+	+	+	+	+	+	+	+
Total	**1.1**	**1.2**	**1.2**	**1.2**	**1.2**	**1.1**	**1.2**	**1.4**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-20: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990	1998	1999	2000	2001	2002	2003	2004
CH_4	**33**	**38**	**37**	**38**	**37**	**34**	**38**	**42**
Wheat	7	6	5	5	5	4	6	5
Rice	4	3	4	4	4	3	5	4
Sugarcane	1	1	1	1	1	1	1	1
Corn	13	17	16	17	16	15	17	20
Barley	1	1	+	1	+	+	+	+
Soybeans	7	10	10	10	11	10	9	12
Peanuts	+	+	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+
Barley	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+
CO	**689**	**789**	**767**	**790**	**770**	**706**	**796**	**877**
Wheat	137	128	115	112	98	80	117	108
Rice	86	65	77	76	77	61	96	75
Sugarcane	18	23	23	24	23	23	22	19
Corn	282	347	336	353	338	319	359	420
Barley	16	13	10	12	9	8	10	10
Soybeans	148	211	204	212	222	212	189	242
Peanuts	2	2	2	2	3	2	3	3
NO_x	**28**	**35**	**34**	**35**	**35**	**33**	**34**	**39**
Wheat	4	3	3	3	3	2	3	3
Rice	3	2	3	3	3	2	3	3
Sugarcane	+	+	+	+	+	+	+	+
Corn	7	8	8	8	8	8	9	10
Barley	1	+	+	+	+	+	+	+

Soybeans	14		20	19	20	21	20	18	23
Peanuts	+		+	+	+	+	+	+	+

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).[9] In order to estimate the amounts of carbon and nitrogen released during burning, the following equations were used:[10]

Carbon Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned *in situ*) × (Dry Matter Content of the Residue) × (Burning Efficiency) × (Carbon Content of the Residue) × (Combustion Efficiency)[11]

Nitrogen Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned in situ) × (Dry Matter Content of the Residue) × (Burning Efficiency) × (Nitrogen Content of the Residue) × (Combustion Efficiency)

Emissions of CH_4 and CO were calculated by multiplying the amount of carbon released by the appropriate IPCC default emission ratio (i.e., CH_4-C/C or CO-C/C). Similarly, N_2O and NO_x emissions were calculated by multiplying the amount of nitrogen released by the appropriate IPCC default emission ratio (i.e., N_2O-N/N or NO_x-N/N).

The crop residues that are burned in the United States were determined from various state-level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data for all crops except rice in Florida and Oklahoma were taken from the USDA's *Field Crops, Final Estimates 1987-1992, 1992-1997, 1997-2002* (USDA 1994, 1998, 2003), and *Crop Production 2004 Summary* (USDA 2005). Rice production data for Florida and Oklahoma, which are not collected by USDA, were estimated by applying average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) to Florida acreages (Schueneman 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005) and for Arkansas (USDA 1994, 1998, 2003, 2005) to Oklahoma acreages[12] (Lee 2003, 2004, 2005). The production data for the crop types whose residues are burned are presented in Table 6-21.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of

[9] The IPCC Good Practice Guidance (IPCC 2000) provided no updates to the methodology for estimating field burning of agricultural residues.

[10] Note: As is explained later in this section, the fraction of rice residues burned varies among states, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

[11] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

[12] Rice production yield data are not available for Oklahoma so the Arkansas values are used as a proxy.

Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level, annual rice production statistics. The annual percentages of rice area burned in each state were obtained from the agricultural extension agents in each state and reports of the California Air Resources Board (Bollich 2000; California Air Resources Board 1999, 2001; Cantens 2005; Deren 2002; Fife 1999; Guethle 1999, 2000, 2001, 2002, 2003, 2004, 2005; Klosterboer 1999a, 1999b, 2000, 2001, 2002, 2003; Lee 2005; Lindberg 2002, 2003, 2004, 2005; Linscombe 1999a, 1999b, 2001, 2002, 2003, 2004, 2005; Najita 2000, 2001; Schueneman 1999a, 1999b, 2001; Stansel 2004, 2005; Street 2001, 2002, 2003; Walker 2004, 2005; Wilson 2003, 2004, 2005) (see Table 6-22 and Table 6-23). The estimates provided for Florida remained constant over the entire 1990 through 2004 period, while the estimates for all other states varied over the time series. For California, the annual percentages of rice area burned in the Sacramento Valley are assumed to be representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). These values declined between 1990 and 2004 because of a legislated reduction in rice straw burning (Lindberg 2002) (see Table 6-23).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum for sugarcane is from University of California (1977). Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue carbon content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The nitrogen content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999). These data are listed in Table 6-24. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types (EPA 1994). Emission ratios for all gases (see Table 6-25) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-21: Agricultural Crop Production (Gg of Product)

Crop	1990	1998	1999	2000	2001	2002	2003	2004
Wheat	74,292	69,327	62,475	60,641	53,001	43,705	63,814	58,738
Rice	7,113	8,414	9,392	8,705	9,794	9,602	9,084	10,495
Sugarcane	25,525	31,486	32,023	32,762	31,377	32,253	30,715	26,576
Corn*	201,534	247,882	239,549	251,854	241,377	227,767	256,278	299,917
Barley	9,192	7,655	5,922	6,919	5,407	4,940	6,059	6,080
Soybeans	52,416	74,598	72,223	75,055	78,671	75,010	66,778	85,484
Peanuts	1,635	1,798	1,737	1,481	1,940	1,506	1,880	1,933

*Corn for grain (i.e., excludes corn for silage).

Table 6-22: Percentage of Rice Area Burned by State

State	1990-1998	1999	2000	2001	2002	2003	2004
Arkansas	13%	13%	13%	13%	16%	22%	17%
California	variable[a]	27%	27%	23%	13%	14%	11%
Florida[b]	0%	0%	0%	0%	0%	0%	0%
Louisiana	6%	0%	5%	4%	3%	3%	3%
Mississippi	10%	40%	40%	40%	8%	65%	28%
Missouri	5%	5%	8%	5%	5%	4%	4%
Oklahoma	90%	90%	90%	90%	90%	100%	88%
Texas	1%	2%	0%	0%	0%	0%	0%

[a] Values provided in Table 6-23.
[b] Although rice is cultivated in Florida, crop residue burning is illegal. Therefore, emissions remain 0 throughout the time series.

Table 6-23: Percentage of Rice Area Burned in California, 1990-1998

Year	Percentage

1990	75%
1991	75%
1992	66%
1993	60%
1994	69%
1995	59%
1996	63%
1997	34%
1998	35%

Table 6-24: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	Carbon Fraction	Nitrogen Fraction	Burning Efficiency	Combustion Efficiency
Wheat	1.3	0.03	0.93	0.4428	0.0062	0.93	0.88
Rice	1.4	Variable	0.91	0.3806	0.0072	0.93	0.88
Sugarcane	0.8	0.03	0.62	0.4235	0.0040	0.93	0.88
Corn	1.0	0.03	0.91	0.4478	0.0058	0.93	0.88
Barley	1.2	0.03	0.93	0.4485	0.0077	0.93	0.88
Soybeans	2.1	0.03	0.87	0.4500	0.0230	0.93	0.88
Peanuts	1.0	0.03	0.86	0.4500	0.0106	0.93	0.88

Table 6-25: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.005
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[a] Mass of carbon compound released (units of C) relative to mass of total carbon released from burning (units of C).
[b] Mass of nitrogen compound released (units of N) relative to mass of total nitrogen released from burning (units of N).

Uncertainty

A significant source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each crop type burned each year. Data on the fraction burned, as well as the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops, as well as among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in published literature. Based on expert judgment, uncertainty in the fraction of crop residue burned ranged from zero to 100 percent, depending on the state and crop type.

Based on expert judgment, the uncertainty in production for all crops considered here is estimated to be 5 percent. Residue/crop product ratios can vary among cultivars. For all crops except sugarcane, generic residue/crop product ratios, rather than ratios specific to the United States, have been used. An uncertainty of 10 percent was applied to the residue/crop product ratios for all crops. Based on the range given for measurements of soybean dry matter fraction (Strehler and Stützle 1987), residue dry matter contents were assigned an uncertainty of 3.1 percent for all crop types. Burning and combustion efficiencies were assigned an uncertainty of 5 percent based on expert judgment.

The N_2O emission ratio was estimated to have an uncertainty of 28.6 percent based on the range reported in IPCC/UNEP/OECD/IEA (1997). The uncertainty estimated for the CH_4 emission ratio was 40 percent based on the range of ratios reported in IPCC/UNEP/OECD/IEA (1997).

The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-26. CH_4 emissions from field burning of agricultural residues in 2004 were estimated to be between 0.2 and 1.7 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 75 percent below and 96 percent above the 2004 emission estimate of 0.9 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to between 0.1 and 1.0 Tg CO_2 Eq. (or approximately 73 percent below and 85 percent above the 2004 emission estimate of 0.5 Tg CO_2 Eq.).

Table 6-26: Tier 2 Monte Carlo Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	Gas	2004 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Field Burning of Agricultural Residues	CH_4	0.9	0.2	1.7	-75%	+96%
Field Burning of Agricultural Residues	N_2O	0.5	0.1	1.0	-73%	+85%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and crops to attempt to identify any outliers or inconsistencies. No problems were found. In addition, this year, calculation spreadsheets were linked directly to source data spreadsheets to minimize transcription errors, and a central, cross-cutting agricultural data spreadsheet was created to prevent use of incorrect or outdated data.

Recalculations Discussion

The crop production data for 1997 through 2001 and for 2002 and 2003 were updated using USDA (2003) and USDA (2005), respectively. Data on the rice area harvested in 2000 in Oklahoma was previously unavailable so the area was assumed to be zero last year; this was revised this year based on new information (Lee 2005). Oklahoma rice data on yields and percentage of harvested area burned were also previously unavailable. Last year, the average rice yield for Florida was used as a proxy. This year it was determined that the average rice yield for Arkansas would be a more appropriate proxy, due to similar geography (Lee 2005). The IPCC default of three percent burned (used last year for Oklahoma) was revised to 90 percent this year because 90 percent is an appropriate assumption when data are not available (Lee 2005).

These changes, summarized in Table 6-27, resulted in a change in emissions estimates for CH_4 and N_2O for all years except 1992. From 1990 to 1997, emission estimates for both CH_4 and N_2O increased by less than 0.05 percent. From 1998 to 2001, emission estimates increased or decreased by less than 0.1 percent. From 2002 to 2003, emission estimates increased or decreased by less than 1 percent.

Table 6-27: Changes and Percent Difference in CH_4 and N_2O Emission Estimates for Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

	CH_4			N_2O		
Year	1990-2003 Inventory	1990-2004 Inventory	Percent Difference	1990-2003 Inventory	1990-2004 Inventory	Percent Difference
1990	0.69	0.69	0.03%	0.37	0.37	0.02%
1991	0.65	0.65	0.02%	0.36	0.36	0.02%
1992	0.76	0.76	0.00%	0.41	0.41	0.00%
1993	0.61	0.61	0.02%	0.34	0.34	0.01%
1994	0.81	0.81	0.01%	0.46	0.46	0.01%
1995	0.66	0.66	0.02%	0.38	0.38	0.01%
1996	0.75	0.75	0.00%	0.42	0.42	0.00%

1997	0.77	0.77	0.00%	0.45	0.45	0.00%
1998	0.79	0.79	0.05%	0.46	0.46	0.02%
1999	0.77	0.77	-0.05%	0.45	0.45	-0.04%
2000	0.79	0.79	-0.02%	0.46	0.46	-0.01%
2001	0.77	0.77	-0.08%	0.46	0.46	-0.04%
2002	0.71	0.71	-0.21%	0.43	0.43	0.01%
2003	0.79	0.80	0.30%	0.44	0.44	0.78%

Planned Improvements

Preliminary research on agricultural burning in the United States indicates that residues from several additional crop types (e.g., grass for seed, blueberries, and fruit and nut trees) are burned. Whether sufficient information exists for inclusion of these additional crop types in future inventories is being investigated.

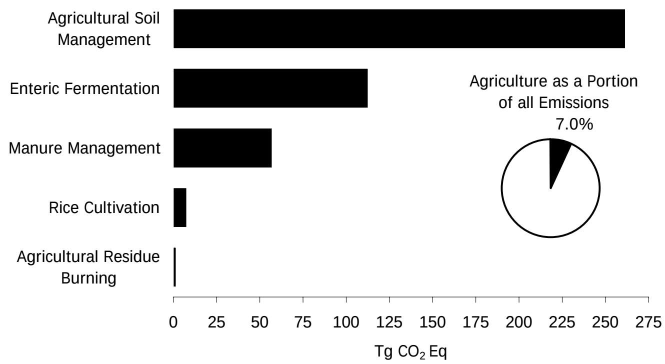
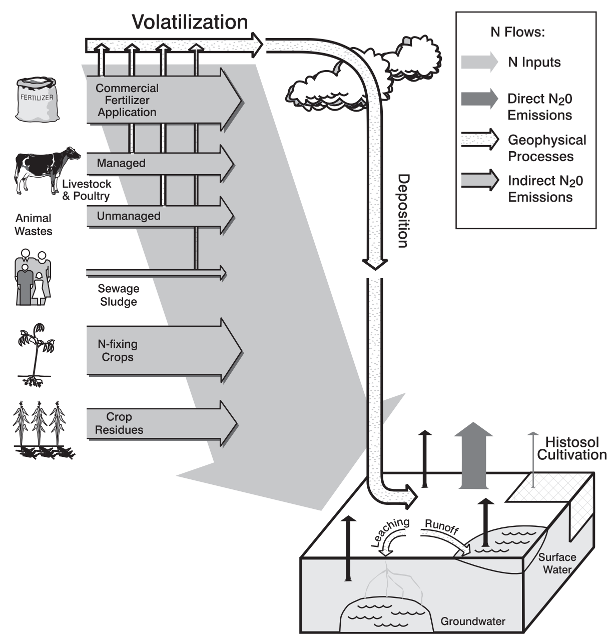


Figure 6-1: 2004 Agriculture Chapter GHG Sources

Figure 6-2

Direct and Indirect N_2O Emissions from Agricultural Soils



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from agricultural soils in the United States. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Descriptions of Figures: Agriculture

Figure 6-1 illustrates the data presented in Table 6-1. Agricultural soil management is the greatest source, responsible for 261.5 Tg CO_2 eq. Agricultural residue burning is the smallest source, accounting for 1.4 CO_2 eq. In addition, there is a pie chart that indicates that agriculture processes made up 7.0 % of U.S. greenhouse gas emissions in 2004.

Figure 6-2 illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from agricultural soils in the U.S. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emissions pathways are also shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.